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THESIS

STATISTICAL ADJUSTMENT OF THE HATRACK
TYPHOON TRACK FORECASTING MODEL

by

Ronald Charles Gilchrist

June 1980

Thesis Advisor: Russell L. Elsberry

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Statistical Adjustment of the HATRACK Typhoon Track Forecasting Model.

by

Ronald Charles Gilchrist
Captain, United States Air Force
B.S., The Pennsylvania State University, 1969

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

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Author ______________________________

Approved by: ______________________________
Thesis Advisor

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Chairman, Department of Meteorology

____
Dean of Science and Engineering

ABSTRACT

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My interest in the difficult problems of "typhoon forecasting" was first prompted by the outstanding instruction of Commander F. R. Williams, U.S. Navy. In the many meteorology laboratories he conducts, Commander Williams not only teaches, he inspires the student to seek new answers.

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I. INTRODUCTION

Each year as many as 40 tropical storms are spawned over the Northwestern Pacific Ocean, and several of them grow to typhoon intensity. Their adverse impact on human activities often includes interruptions of military operations. However, preparations in response to accurate meteorological warnings can alleviate the damage from these storms.

Ships on the open water are especially vulnerable to the damaging winds and high seas generated by tropical storms. Ship captains must always be ready to take early evasive action, and an accurate forecast of the storm's future path assumes incalculable value. Yet tropical storm track forecasting is one of the most difficult problems that challenges the skills of the meteorologist.

Primary responsibility for issuing Northwestern Pacific tropical cyclone warnings rests with the Joint Typhoon Warning Center (JTWC) on Guam. The Center has access to several computer models which generate storm track forecasts to guide their decisions. Yet no single model renders accurate forecasts consistently, and errors on the order of hundreds of nautical miles occur with unfortunate frequency.

Efforts to achieve a perfect model are frustrated by lack of perfect knowledge of important conditions: the locations of storms are usually difficult to pinpoint, measurements of significant meteorological elements inside the storms are difficult or impossible to obtain, and the state of the tropical Pacific atmosphere which drives the storm must be inferred from sparse observations. A fully deterministic method of

forecasting tropical storm tracks may continue to elude the scientist. However, if the model errors occur with reasonable regularity, then statistical tools can be applied to improve the model's output.

A technique of statistically adjusting dynamical forecasts of tropical cyclone motion has been tested by Frill (1979). Using the facilities of the U.S. Navy Fleet Numerical Weather Central (now renamed the Fleet Numerical Oceanography Center or FNOC), operationally analyzed data were obtained through forward and backward integrations of the FNOC Tropical Cyclone Model (TCM). Forecast parameters for numerous storms were then offered as predictors in a multivariate regression scheme to obtain equations to correct a systematic bias demonstrated by the TCM. Results showed that the equations produce improvements over the unmodified model predictions at all forecast intervals.

At the same time, Frill's work shows that regression equations built from small samples can result in forecasts that are worse than the unmodified output of the TCM. Efforts to enlarge the sample by generating data from individual storms is hampered by the fact that the TCM is a three-layer, primitive equation model that requires approximately 15 minutes of computer time to execute. Some economy of computer time was gained through creating several cases from the same data stream by using a sequence of initial times for each storm. While the regression equations provided improvements in the track forecasts, the longer lasting storms may have had unwarranted influence during the regression analysis. The statistical independence of each case may have been questionable.

The most economical method to obtain larger samples with a better guarantee of independence would be to use a model that executes in less time. Such an opportunity is found in the FNOC Hurricane and Typhoon Tracking (HATRACK) model. This model, together with the Modified Hurricane and Typhoon Tracking (MOHATT) model which invokes another type of bias correction, is driven by a program named CYCLOPS. This program executes both models in approximately one-third of the time required by the TCM. Thus larger samples, with each case derived from a separate storm, can be obtained from the CYCLOPS program with a comparatively modest investment of computer time.

The primary objective of this thesis is to develop equations through a multivariate linear regression analysis of data from forward and backward integrations of the HATRACK model where each case is derived from a single storm. The resulting modified forecasts are tested to determine whether improvements over the MOHATT bias correction can be achieved.

II. DESCRIPTION AND USE OF THE MODELS

A. THE HURRICANE AND TYPHOON TRACKING (HATRACK) MODEL

Development of the HATRACK model began in 1965 at FNOC and the Naval Postgraduate School. The model was designed to require less computer time than other existing models by taking advantage of the numerically analyzed operational products of FNOC. Pioneer work was performed and reported by Renard (1968).

In the HATRACK model, the input storm is represented as a point vortex on a grid. A steering flow for the vortex is derived from a current analysis and the 12 to 72-hour prognoses which are generated by the FNOC hemispheric prediction model. The analysis and prognoses data are "D" fields (deviations from standard heights) for any of several pressure levels of the atmosphere. For the operational program, the requesting forecaster may decide which level for steering flow is the most appropriate for a given situation or may request separate forecasts from as many as three levels. In the model, the "D" values are transformed into SR fields by filtering the shorter waves. The term SR arises from the FNOC Scale and Pattern Separation program where short waves are labeled "SD" and long waves are labeled "SR". The filter effectively removes the average size cyclone from the field, and the results are used to compute geostrophic SR winds. A modification of the sine function in the geostrophic equation is made below 30° N to avoid difficulties with values of the Coriolis parameter which would normally approach zero at the equator. The resulting pseudo-geostrophic SR winds represent the steering flow

which is used to advect the point vortex which represents the storm. The advection provides position forecasts at six-hour intervals to 72 hours from the initial time. Additional details of the operational HATRACK model are given in the U.S. Naval Weather Service Numerical Environmental Products Manual (1975) and both the Operator's Manual and the Maintenance Manual for Tropical Cyclone Forecasts Program (1978).

A research version of the HATRACK program was kindly provided for this study by the Systems and Applied Sciences Corporation, the primary Navy contractor for the HATRACK program. This version differs from the operational program in the filter that is used to convert the "D" values to SR fields. The operational program uses a five-point Laplacian filter while the research version uses a modified filter known as LPF65F. Tests of the HATRACK program using analyzed "D" values as input in place of the prognoses from the FNOC hemispheric model were performed to evaluate the behavior of the two filters. The results showed that position forecasts produced by the LPF65F differed from those produced through use of the five-point Laplacian filter by one degree or less at all time intervals. The operational filter requires approximately five times the computer time as does the LPF65F filter. In the interest of economy, the research model with the LPF65F filter was used for this study; and it is believed that use of this version does not invalidate the results of this study.

B. THE MODIFIED HURRICANE AND TYPHOON TRACKING (MOHATT) MODEL

The first tests with the HATRACK model (Renard, 1968) suggested a consistent error in both the zonal and meridional components of the model's steering forecasts. Further evidence of bias in the HATRACK model and possible methods of correction were revealed in subsequent studies (Renard and Levings, 1969). A bias correction scheme was later refined and incorporated into a program which is now the MOHATT model (Renard et al; 1970, 1972 and 1973).

The MOHATT model commences an unmodified HATRACK steering at 12 hours prior to the initial time and requires that the storm positions for -6 and -12 hours be input by the forecaster. Forecast positions produced from -12 hours to the initial time are then compared to the known positions which were input to the model. Errors in the forecasts up to the initial time are used in an empirical-statistical scheme to provide a correction which is extrapolated forward to produce modified HATRACK forecasts at 24, 48 and 72 hours.

The MOHATT model uses the same filter as that chosen for the HATRACK model. Therefore, comparison of regression modified HATRACK forecasts with MOHATT forecasts is not impaired by use of the research model. Further details of the MOHATT model are found in the same manuals cited above for HATRACK.

C. FORWARD INTEGRATIONS WITH THE MODELS

The HATRACK and MOHATT models are driven by a parent program named CYCLOPS. Thus both are run at the same time using a common set of data,

and both can be executed in the prognoses mode (described above) or in the analysis mode.

This study utilizes data from storms which occurred during the years 1967 to 1974. The predicted wind fields over the Northwestern Pacific Ocean for that time period were not archived. However, analyzed fields of "D" values were archived at FNOC. The Systems and Applied Sciences Corporation had earlier extracted these fields, and they kindly made magnetic tape copies available for this study. These analyzed fields might have been used to recreate the required predicted "D" fields through use of the FNOC primitive equation model, but this method would demand a prohibitive amount of computer time to obtain a sample of reasonable size.

Instead, the analysis mode was used for this study wherein analyzed "D" fields are substituted for predicted values. This technique is commonly referred to as "perfect prog" since the analyzed fields can be viewed as forecast fields that verified perfectly. This method suffers the drawback that biases present in the primitive equation model which provides forecast data to the operational CYCLOPS program cannot be corrected by a regression analysis. Instead, only the biases present in the HATRACK model can be studied.

D. BACKWARD INTEGRATIONS WITH THE MODELS

The purpose of performing backward integrations is to generate parameters with which to relate past performance of the HATRACK model to future performance so that a correction can be made. The parent CYCLOPS program makes use of several subroutines whose interrelations are complex

and often subtle; a modification in one subroutine can result in a myriad of problems in another. To avoid the risk of changing the nature of the program, extensive modifications to force HATRACK to perform backward integrations were not made for this study.

Instead, a much simpler approach was taken. The "D" values are requested starting from the initial time to -72 hours, but then a routine is run to change the date-time groups to bogus times which appear in the forward mode. The CYCLOPS program is then given a matching initial time and the bogused "D" values. One change is made within the HATRACK model to reverse the sense of movement of the storm. Thus the model, while seemingly running in the forward mode, is using information which steps backward in time; and the model is in effect integrating backwards. This routine is easily verified: one runs the model forward to +72 hours, then uses the forecast at +72 hours for an initial position input to the bogus time routine and runs backward 72 hours to the original time. The two paths thus forecast should coincide. Several tests of this routine were made, and all paired paths coincided except for random differences on the order of 0.1 degrees of latitude and longitude. These small differences may be attributed to round-off error.

Backward integrations of the MOHATT model were not desired for this study. In the bogus time runs to obtain backward integrations of HATRACK, the MOHATT portion was excluded by simply omitting the request for MOHATT forecasts from the input to the CYCLOPS program.

III. APPROACH TO REGRESSION ANALYSIS

A. THE PREDICTORS AND PREDICTANDS

Storm positions at each forecast time are to be adjusted by two regression equations: one for the east-west direction and another for the north-south direction. Thus for each HATRACK forecast run, a total of 12 equations would be used to modify storm positions in 12-hour increments from 12 to 72 hours. Another method was possible since HATRACK provides forecasts at six-hour intervals. However, it was felt that the six-hour positions might be so close together that the uncertainty associated with best track positions might overlap and render the predictand computations meaningless. Therefore this study adheres to the 12-hour interval used by Frill (1979).

Using the HATRACK forecasts versus best track positions (see Fig. 1), 12 predictands were derived by computing the east-west and north-south differences between positions at corresponding times. The best track data are positions determined during post-storm analysis. The Systems and Applied Sciences Corporation provided a copy of the best track positions used in this study.

Predictors subjected to the regression analysis were model predicted velocity from forward integrations and both displacement and velocity from backward integrations. These parameters were broken into components along the east-west and north-south directions. The Julian day and the latitude and longitude of the initial position of each HATRACK forecast run were also included as predictors in the regression equations. The

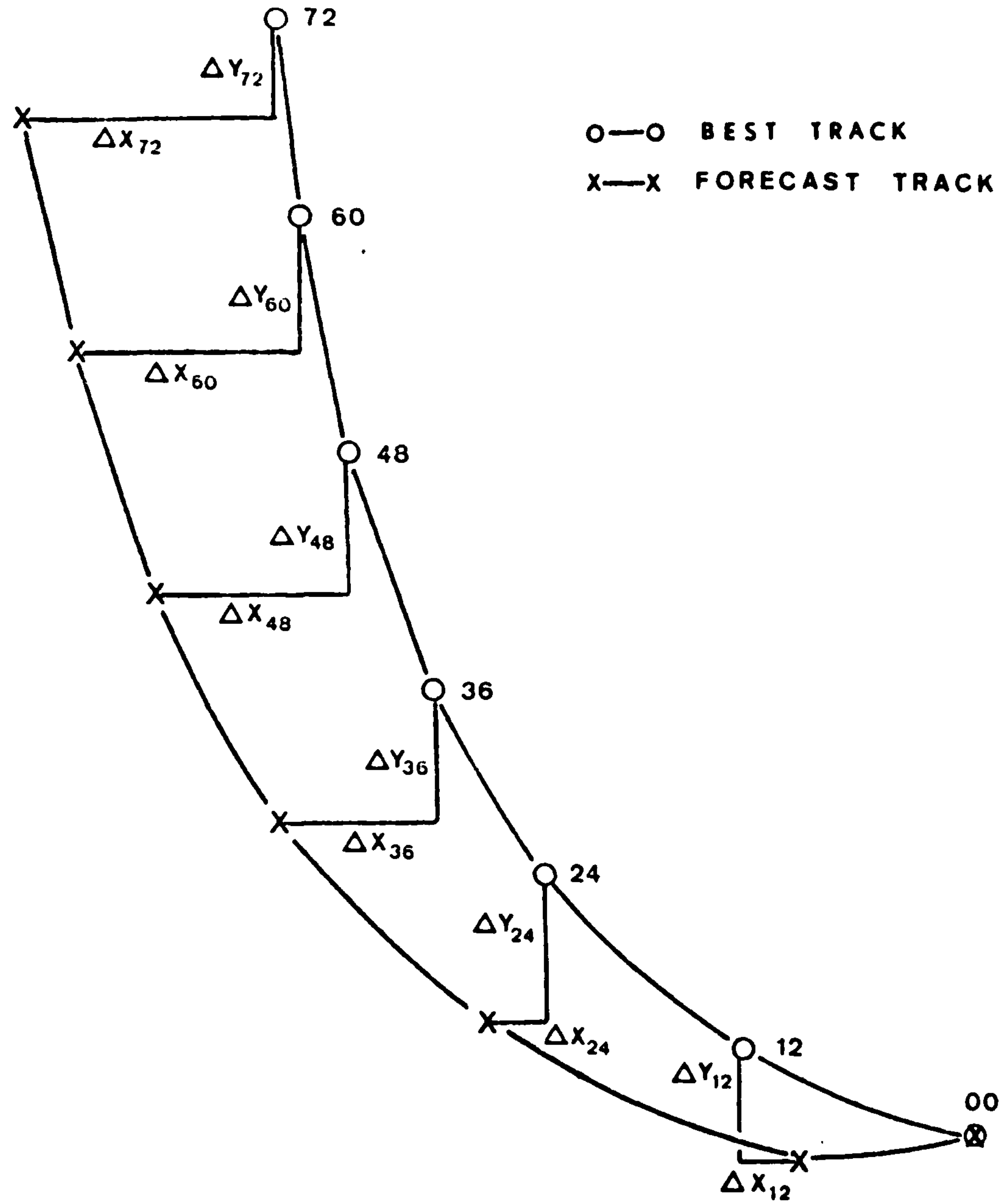

Figure 1. Depiction of the model errors (i.e., the predictands), which are the differences between the best track and forecast positions, which are shown above as ΔX_{12}, ΔY_{12}, ΔX_{24}, ΔY_{24}, etc.

HATRACK model does not include any parameter related to the size of the storm, which may contribute to bias in the forecasts. It seems reasonable that storms of different sizes will be advected with different efficiency by the same wind field. Unfortunately, no parameter relating to the vertical extent of each storm is archived. However, the radius of each storm, defined as the distance from storm center to outermost closed isobar, at the initial time is included as a predictor. Information on the radii of storms was kindly provided by the Naval Environmental and Prediction Facility. A schematic illustration of the displacement predictors and the intervals over which the velocity predictors were calculated is shown in Fig. 2. A complete list of predictands and predictors, with the times for which they were computed, appears in Table I.

B. PREPARATION OF DATA

Certain economies exist in the CYCLOPS program when used in the analysis mode that allow computations of HATRACK and MOHATT forecasts at three levels for a modest increase in computer time over that required for a single level. It was therefore feasible to obtain forecasts for three levels for each case used in this study. The levels chosen were 850, 700 and 500 mb.

The Numerical Environmental Products Manual (1975) indicates that 700 and 500 mb computations in the HATRACK and MOHATT models render more accurate forecasts than do other levels in the Northwestern Pacific Ocean. Yet the forecasts based on 700 and 500 mb can differ markedly, and there is no objective rule to guide the forecaster in his choice. Also, the

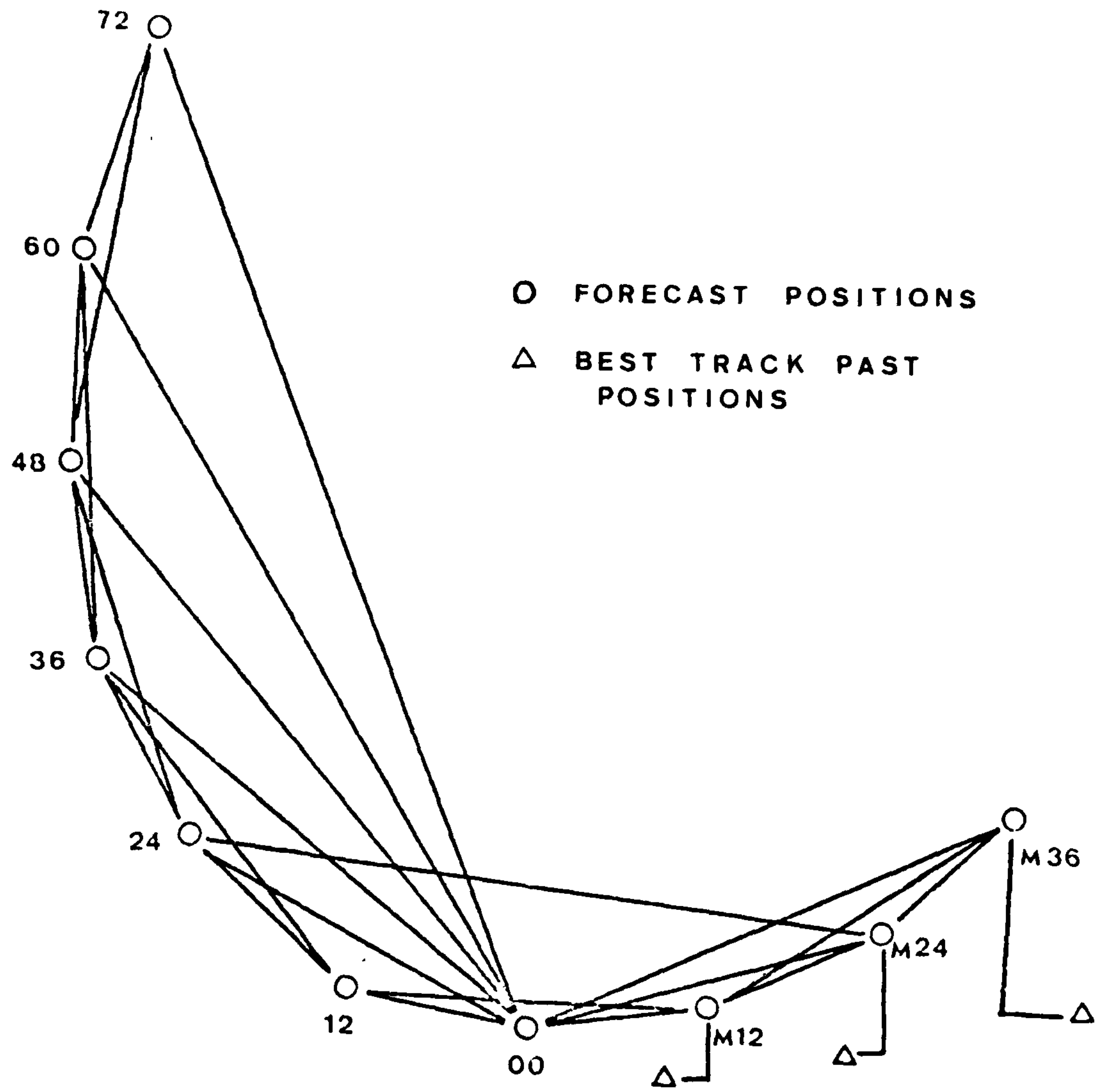

Figure 2. Depiction of intervals over which velocities (average speeds) were computed using forward and backward integrations of the HATRACK model, and displacements (predictors) computed from backward integrations.

TABLE I

Predictors/predictands used to develop regression equations for HATRACK forecast modification.

1. Predictands: $\Delta X, \Delta Y$

   Times at which predictands are computed:

   12, 24, 36, 48, 60, 72 hrs

2. Predictors: $\Delta X, \Delta Y$, u, v

   Time intervals over which each velocity predictor was calculated from forward integrations:

   00-12, 12-24, 24-36, 36-48, 48-60, 60-72,

   00-24, 12-36, 24-48, 36-60, 48-72, 00-36,

   00-48, 00-60, 00-72 hrs

   Time intervals over which each velocity predictor was calculated from backward integrations:

   00-M12, M12-M24, M24-M36, 12-M12,

   00-M24, M12-M36, 00-M36, 24-M24 hrs

   where 00 = initial time
   M = minus (designating pre-initial time)

3. Initial Position Predictors: Julian Day, Latitude, Longitude, Storm Radius

   Times: Initialization time of a given HATRACK forecast run.

Systems and Applied Sciences Corporation personnel stated that 500 mb steering appears from their experience to be the best performer over a long period of time. Therefore comparison of the forecasts from 700 and 500 mb becomes an interesting addition to this study. The third level is a choice between data which are available for 850 and 250 mb. Since the vertical extent of tropical storms is variable, the lower level winds might be expected to play a more important role in the advection of the storm. Therefore, the 850 mb level was selected for this study.

Individual forecasts for 92 storms over the Northwestern Pacific Ocean from the years 1967 to 1974 were produced. The storms selected are those for which sufficient best track and "D" value data exist to allow computation of forward trajectories to 72 hr and backward trajectories to 36 hr as shown in Fig. 1 and Fig. 2. Where ample data allowed a choice of initial times, an auxiliary randomization process of die tossing was used to guide the choice. This random process was used to avoid biases in the sample which might have resulted if other criteria, such as storm track behavior, were used to select the initial time.

Approximately one-third of each year's storms were randomly selected to form an independent sample of 31 reserved for testing the regression equations. The same 31 storms were included in the independent sample for each level (500, 700 and 850 mb) to permit comparisons between the three levels.

The remaining 61 storms were used to form dependent samples at each level for the regression analysis. The HATRACK and MOHATT models will

not forecast movement of a storm below 5°N. In one case, 850 and 700 mb steering forecasts were produced but 500 mb forecasts were not produced due to an abortive 5°N crossing. Thus the sample at 500 mb is reduced to 60 storms versus 61 at 700 and 850 mb. Also, one case produced HATRACK forecasts, but no MOHATT forecasts were produced due to proximity of 5°N. This latter storm was purposely included in the dependent samples since MOHATT forecasts are not required for the regression analysis. This departure from randomness in forming the independent sample was made to maintain an equivalent sample size for each model to permit comparisons between MOHATT forecasts and regression modified HATRACK forecasts. No other departures from randomness were required.

C. METHOD OF EQUATION DERIVATION

Separate regression equations for the 850, 700 and 500 mb levels were derived from the dependent samples using the University of California BMPD Biomedical Computer Program (Dixon and Brown, 1977) stepwise regression routine. All predictors listed in Table I were offered to the regression routine for inclusion in each regression equation. The Biomed routine computed the R^2 parameter in the normal mode and used default values of F-to-enter and F-to-remove. Selection of predictors for each equation was limited to five because selection of predictors beyond five each added less than 0.02 to the R^2 parameter. An experiment was performed with 500 mb data to compare the efficiency of equations limited to five predictors with equations that included all predictors selected by the BMPD regression routine. In the longer equations, the smallest

addition to R^2 through inclusion of another predictor was 0.0086, and the largest number of predictors selected by the BMPD routine was eight. The two sets of equations were then applied to the independent 500 mb sample to produce two sets of modified HATRACK forecasts. Comparison of the two sets of forecasts thus obtained showed only small differences, on the order of round-off error, with some forecasts being improved and others deteriorated by the inclusion of more than five predictors. It is therefore concluded that the extra predictors reflect noise that is present in the samples and that inclusion of predictors beyond five does not add to the quality of the regression equations.

D. NOTATION AND USE OF REGRESSION EQUATIONS

It is convenient to refer to predictors and predictands by the variable names actually used in the computer programs. An example of a regression equation follows:

$$\begin{aligned} \text{DYER60} = &+51.8976 - 5.3261\ (\text{XXLON}) - 2.8611\ (\text{BYER12}) \\ &- 15.3362\ (\text{VY0072}) + 9.0203\ (\text{VXM4M2}) \end{aligned}$$

Here the predictant DYER60 is the north-south error in nautical miles (best track minus forecast position as in Fig. 1) at +60 hr. The predictor XXLON is the initial longitude. BYER12 is the "back forecast" north-south error in nautical miles at -12 hr, as in Fig. 2. VY0072 is the north-south component of the velocity (average speed in nautical miles per hour) computed from the initial time (00) to +72 hr. The predictor VXM4M2 is the east-west component of the velocity (average speed in nautical miles per hour) from -24 to -12 hr. The predictor RADIUS is given in whole degrees of latitude.

Westward and northward motions are considered positive, and all error computations are best track minus forecast position. Therefore, negative errors indicate forecast positions west or north of best track. Complete sets of the regression equations derived in this study for 500, 700 and 850 mb are given in Appendices A, B and C respectively.

When the regression equations are applied to modify HATRACK forecasts, predictors are provided in the same units noted above. The predictands are thus computed in nautical miles and then converted to degrees of longitude or latitude as appropriate. The results are added to the forecast positions to adjust them toward the best track.

For ease in reference and display of data, it is convenient to refer to the regression technique as STATRAK for "Statistical Tracking." In the remainder of this report, the regression equation modification of the HATRACK model is referred to as the STATRAK model.

IV. RESULTS

A. AT 500 MB

A test with 59 storms from the 500 mb dependent sample confirmed that a systematic bias is present in the HATRACK forecasts (see Fig. 3). One storm from the group of 60 was not included in the test due to the absence of MOHATT forecasts, as explained earlier. In this sample, the HATRACK output contains considerable bias in the east-west direction, but displays very little bias in the north-south direction before 48 hr. Thus the HATRACK model at 500 mb appears to move the storm too slowly in the

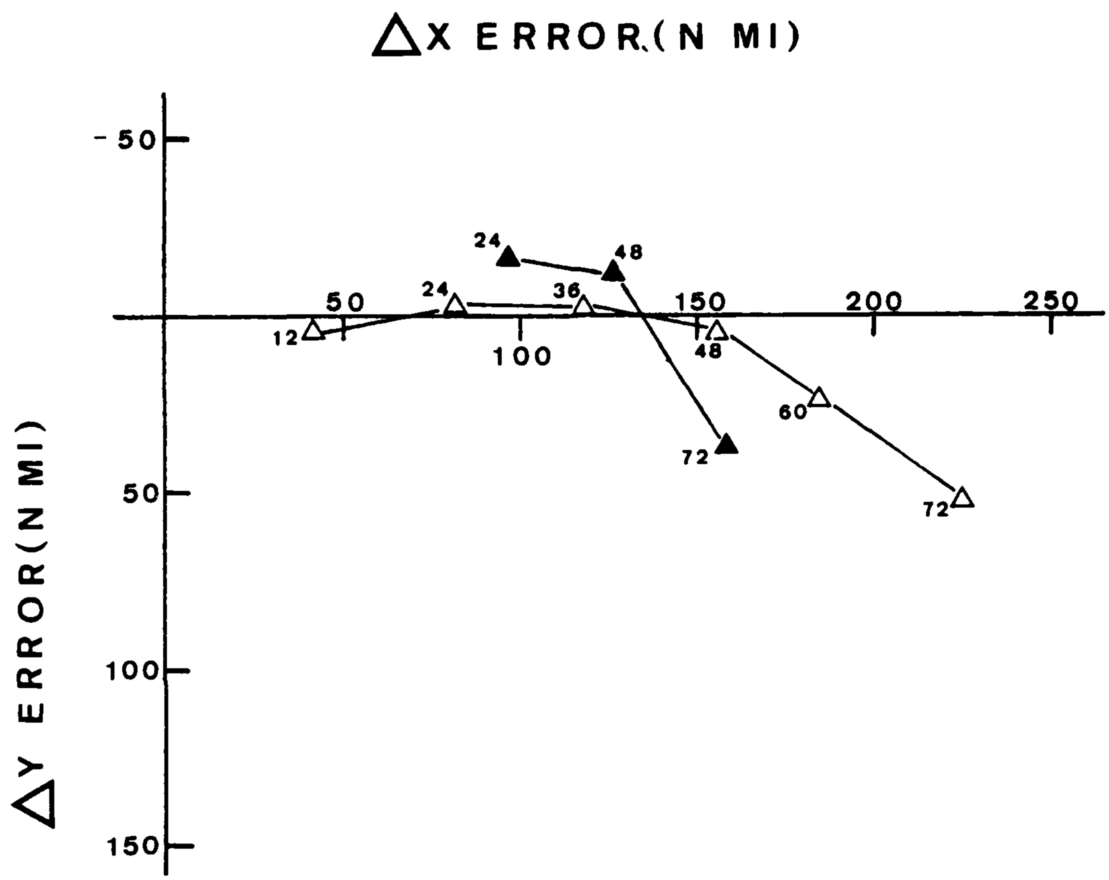

Figure 3. Mean errors of the HATRACK model (△) and the MOHATT model (▲) in component form calculated from the 500 mb dependent sample.

westward direction at all times, and too slowly in the northward direction from 48 to 72 hr. For the normal storm track toward the northwest, this would lead to forecasts that were slow and to the left of the actual track.

For this dependent sample, the MOHATT model fails to correct the HATRACK east-west bias at 24 hr but attains notable reductions of the east-west bias at 48 and 72 hr. The MOHATT model actually introduced a small amount of bias by enlarging the north-south errors at 24 and 48 hr where HATRACK had little bias. This possibly reflects a weakness of the MOHATT model in applying a bias correction where little or no bias exists.

The test (see Fig. 4) with the 31 storm independent sample shows a different HATRACK forecast bias than in the dependent sample. Comparing the two samples, the HATRACK model exhibits moderately less east-west bias in the independent sample, although the differences out to 48 hr may not be significant. The major difference is that the HATRACK bias in the north-south direction is substantially increased in the independent sample. The MOHATT model failed to reduce the bias of either component at 24 hr in the independent sample, but it did reduce the bias of both components at 48 and 72 hr.

Since the two tests indicate markedly different biases, one might expect that regression equations would not render favorable bias corrections of the independent sample. Yet the STATRACK forecast errors, also shown in Fig. 4, demonstrate considerable skill in removing the east-west HATRACK bias as well as much of the north-south bias.

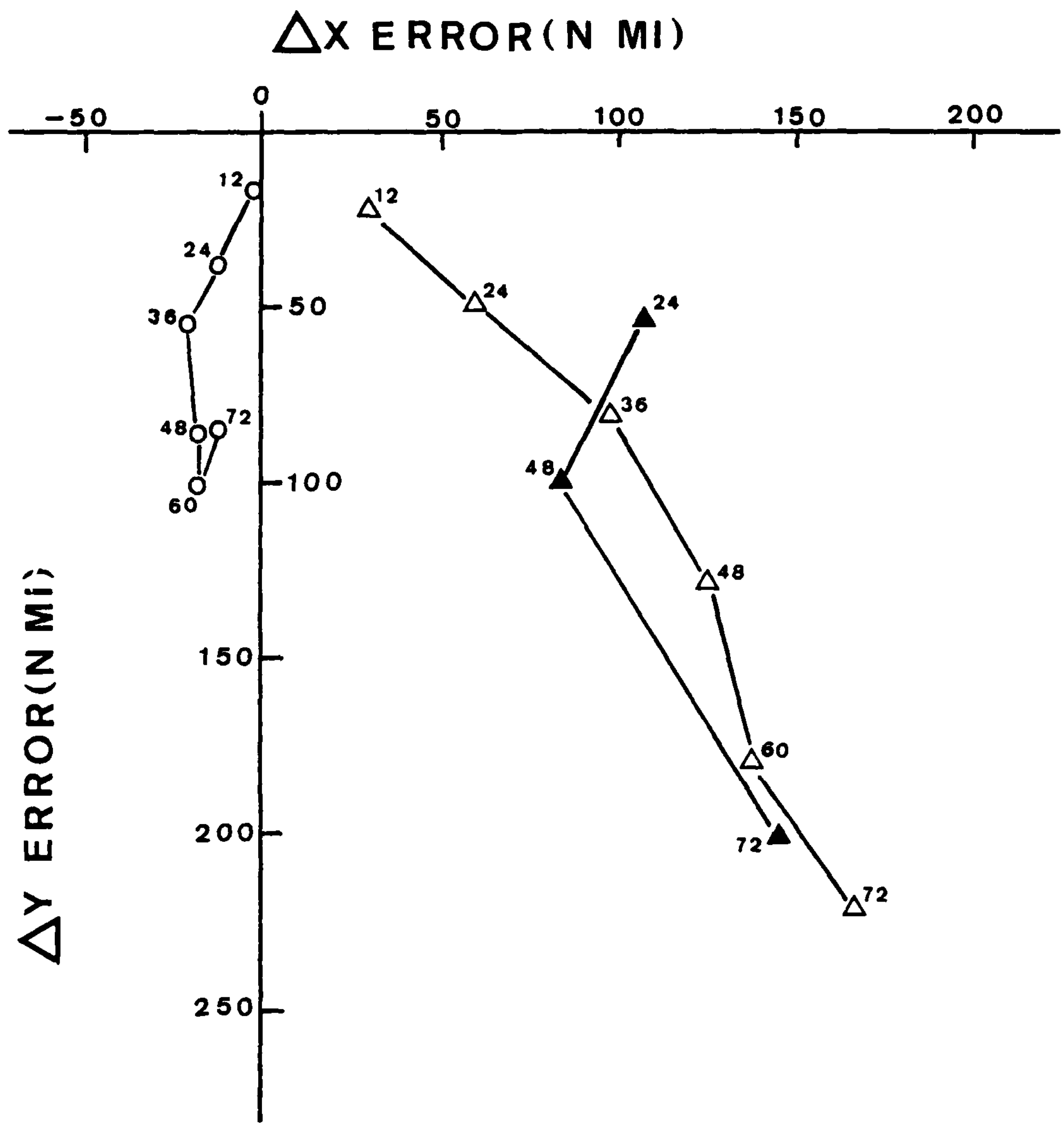

Figure 4. Mean errors of the three models in component form calculated from the 500 mb independent sample relative to best track positions. The plots for HATRACK errors (△) and MOHATT errors (▲) indicate a systematic bias. The plots for STATRAK errors (O) show a reduction of the bias.

The auspicious skill of the STATRAK model, despite differences in the samples, might be explained by the fact that predictors computed from backward integration data appear in every 500 mb regression equation (see Appendix A). The most frequently selected predictor was BYER12 (backward forecast north-south error at -12 hr). Also, the BYER12 predictor made the largest contribution to R^2 of all predictors selected in every north-south predictand equation. It is along this north-south component that the independent sample displayed considerable HATRACK bias while very little appeared in the dependent sample. Apparently the regression scheme has skill in reducing bias by relating future performances of the HATRACK model to its past performance.

The initial latitude position (XXLAT) appears in all but one of the east-west predictand equations. Selection of the XXLAT predictor did not dominate the contribution to R^2 over other predictors in any of the equations. Except for DXER12, where XXLAT does not appear, each of the east-west predictand equations is dominated in terms of R^2 contribution by predictors computed from forward integration data. These results suggest that the east-west velocity of storms has a moderate, yet consistent, latitudinal dependence. This dependence may be an indication that storms are more likely to recurve (i.e. change from westward to eastward motion while also moving north) at higher latitudes.

It is instructive to note that the regression equation for the DXER12 predictant has an R^2 value of 0.26 which is considerably lower than the next smallest R^2 value of 0.46 (associated with DXER60).

Examination of Fig. 3 reveals that a moderate amount of east-west bias was available for the DXER12 predictant to remove. Even with the low value of R^2 for the DXER12 equation, nearly all of the east-west bias at 12 hr was removed in both the dependent and independent samples. It was not convenient to plot the STATRAK results for the dependent sample in Fig. 3 since all values are clustered about the origin as expected. This examination of DXER12 suggests that R^2 should not be used as the only measure of the goodness of the regression equations.

An overall picture of the performance of the STATRAK equations is provided by the means of the error vector lengths (see Fig. 5). This length is computed from the individual storm components, and then the sample average is taken as the estimator of the mean. The STATRAK model provided a smaller mean error vector than those of both HATRACK and MOHATT for every time interval. The plots of STATRAK mean errors from the dependent sample, shown in Fig. 5, might represent the mean limit of the amount of bias that the regression equations can remove.

Details of these mean errors and associated standard deviations are given in Table II. Each standard deviation used in this study was computed as the positive square root of the unbiased estimator of the variance. The STATRAK model provided smaller standard deviations of the error vectors at all intervals except 48 hr where the MOHATT and STATRAK values are equal. The smaller standard deviations are a desirable feature as they indicate that a larger number of values in the sample appear

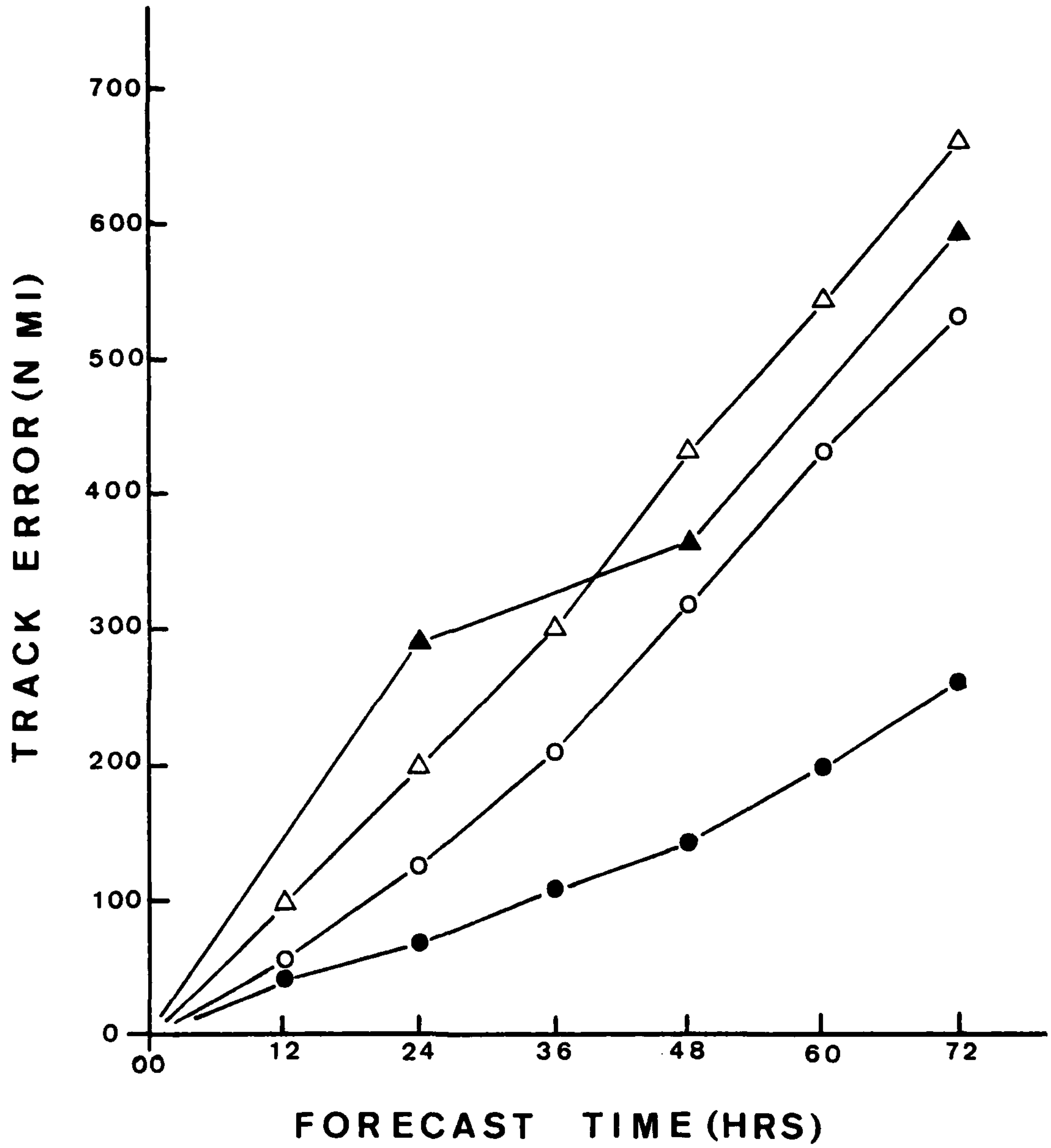

Figure 5. Means of the error vector lengths calculated from the 500 mb independent sample for HATRACK forecasts (△), MOHATT forecasts (▲), STATRAK forecasts (○), and from the 500 mb dependent sample for STATRAK (●).

TABLE II

The means and standard deviations (n mi) of the errors computed from the 500 mb independent sample.

	HATRACK		MOHATT		STATRAK	
	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
12 hr	99	52	--	--	56	44
24 hr	199	103	290	158	124	84
36 hr	302	163	--	--	208	121
48 hr	433	225	364	193	317	193
60 hr	543	284	--	--	432	246
72 hr	661	314	593	287	533	273

close to the mean. That is, there are fewer large individual errors in the sample of STATRAK forecasts than in either of the samples of MOHATT or HATRACK.

The means of the components of error from the independent sample, shown in Fig. 4, are given in detail with associated standard deviations in Table III. The HATRACK north-south means and standard deviations are both larger than those of the east-west components at 48 and 72 hr. These results suggest that the HATRACK bias grows more rapidly in the north-south direction. Comparison with MOHATT component parameters reveals that STATRAK provides both improved means and standard deviations except for the east-west standard deviation at 72 hr. This one exception may be due to chance, as later examination of results at 700 and 850 mb may suggest (see Tables V and VII). Comparison of the two STATRAK components show smaller means for the east-west direction but smaller standard deviations for the north-south components. To appreciate the importance of the standard deviation, one needs only to examine the ranges of STATRAK errors at 72 hr. The east-west range within one standard deviation at 72 hr would be -13 $\pm$ 498 or -511 to 485 nautical miles. Similarly the STATRAK north-south range at 72 hr would be -251 to +421 nautical miles. Thus while the east-west mean is smaller, the north-south component of STATRAK at 72 hr offers a more desirable range of errors in this sample.

TABLE III

The means and standard deviations (n mi) of the components of errors computed from the 500 mb independent sample.

EAST-WEST ERROR (N MI)

	HATRACK		MOHATT		STATRAK	
	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
24 hr	63	136	113	186	-13	104
48 hr	130	310	87	292	-19	279
72 hr	171	470	150	454	-13	498

Note: Positive values indicate forecast east of best track

NORTH-SOUTH ERROR (N MI)

	HATRACK		MOHATT		STATRAK	
	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
24 hr	48	164	54	247	38	103
48 hr	129	336	101	266	86	236
72 hr	223	498	205	416	85	336

Note: Positive values indicate forecast south of best track.

B. AT 700 MB

A test with 60 storms from the 700 mb dependent sample revealed a systematic bias in the HATRACK forecasts (see Fig. 6). As was the case at 500 mb, one storm from the dependent sample was not included due to the absence of MOHATT forecasts. At the 700 mb level, the HATRACK output contains bias in both components with the greatest amount of bias appearing in the east-west direction. There is a notable reduction of HATRACK north-south bias after 48 hr.

In this dependent sample, the MOHATT model again fails to correct the east-west bias at 24 hr, but attains reductions of bias at 48 and 72 hr. The MOHATT model introduces more bias by enlarging the north-south errors at all time intervals.

The test (see Fig. 7) with the 31 storm independent sample reveals a markedly different north-south HATRACK bias than in the dependent sample. The independent sample shows more regularity in the HATRACK north-south error with no improvement after 48 hr in contrast to the dependent sample. Also the sense of the HATRACK north-south error is reversed. In the dependent sample the HATRACK model appears to move storms too rapidly northward, whereas it moves the storms too slowly northward in the independent sample. The sense of the HATRACK east-west error is the same in both samples, but the magnitudes are smaller at all time intervals in the independent sample.

While reducing the north-south error, the MOHATT model has a larger east-west bias at 24 hr. The MOHATT model shows a reduction of bias in both components at 48 and 72 hr.

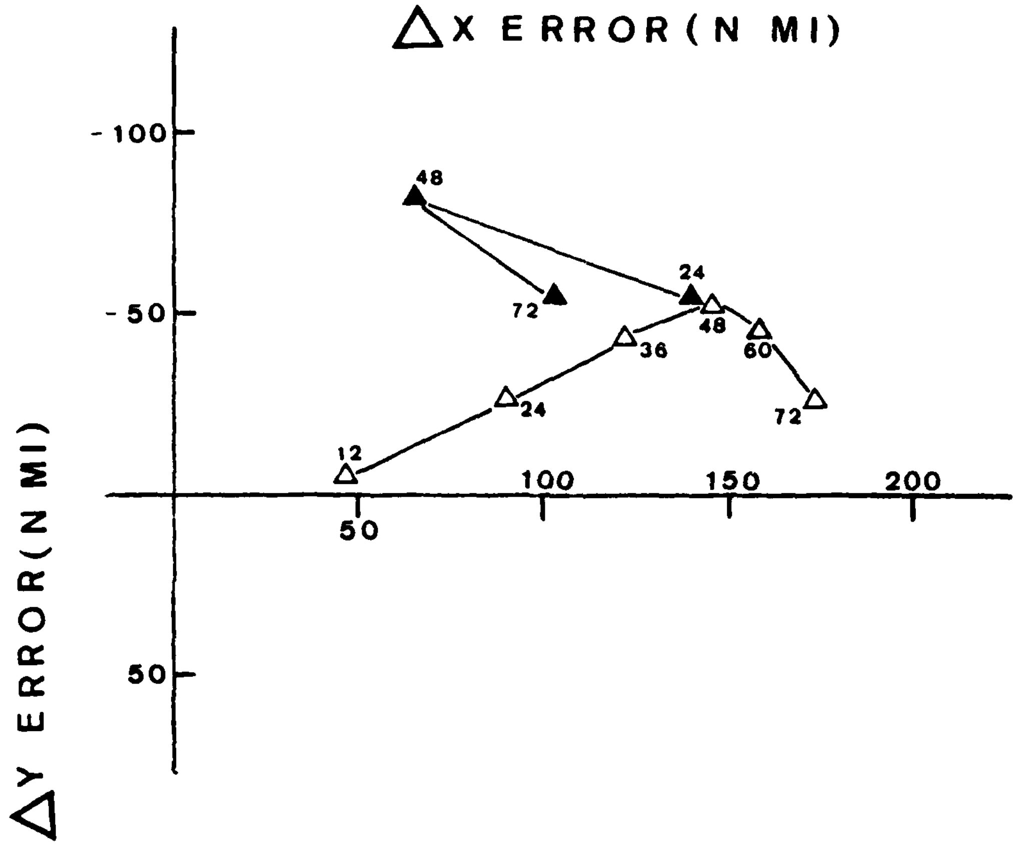

Figure 6. Mean errors of the HATRACK model (△) and the MOHATT model (▲) in component form calculated from the 700 mb dependent sample.

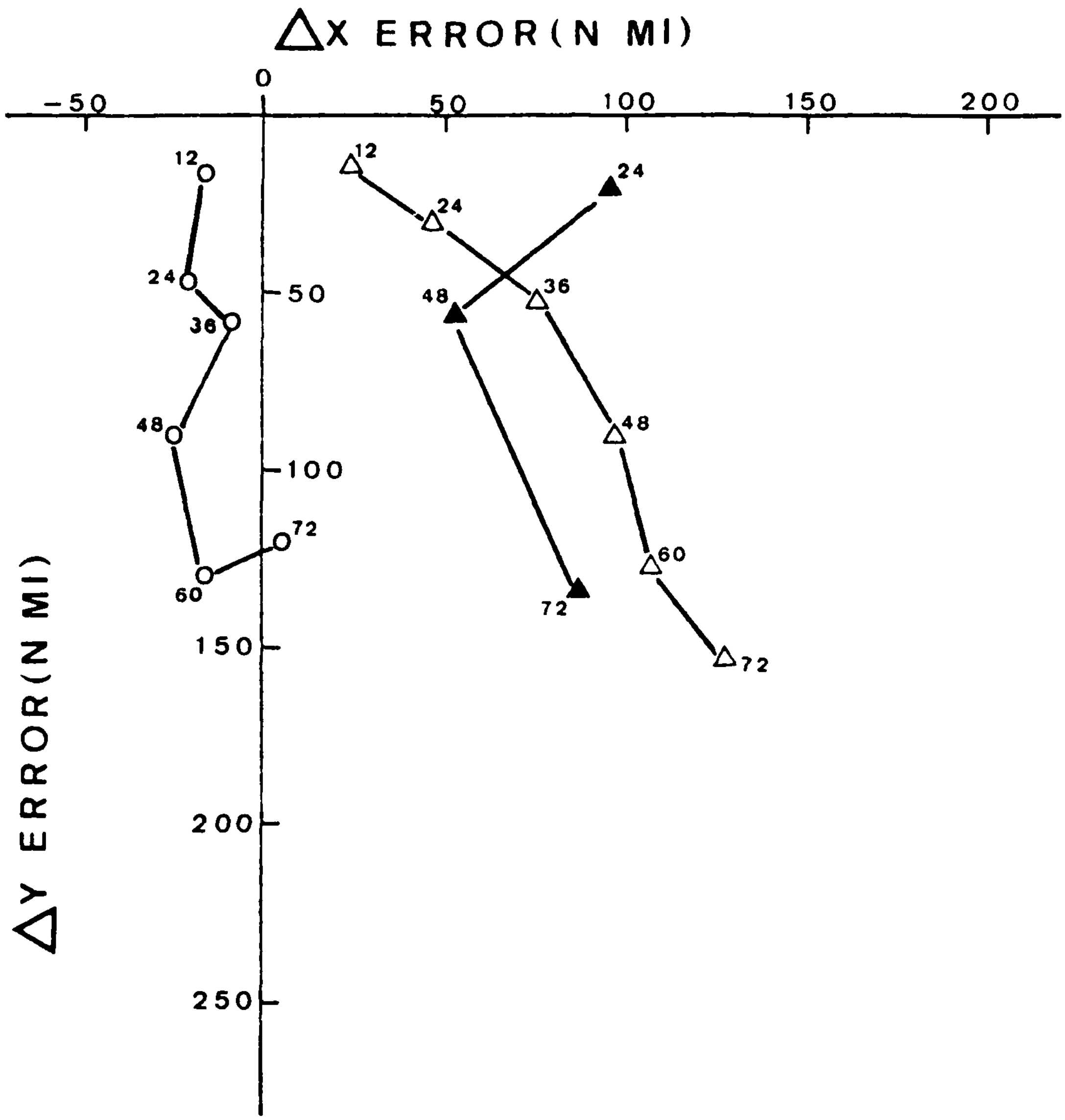

Figure 7. Mean errors of the three models in component form calculated from the 700 mb independent sample relative to the best track positions. The plots for HATRACK errors (Δ) and MOHATT errors (▲) indicate a systematic bias. The plots for STATRAK errors (●) show a reduction of the bias.

The STATRAK forecast errors, also in Fig. 7, indicate skill in removing the east-west bias, but the model apparently fails to reduce north-south bias except at 72 hr. Considering the differences between the north-south biases for the dependent and independent samples (Figs. 6 and 7), it is not surprising if the STATRAK model has less skill along this component. However, such a conclusion should not be accepted before examining both the means and the standard deviations (Table IV). Although the mean north-south errors were not improved at 24 and 48 hr, the associated standard deviations were improved. To compare the results, one needs to compute the ranges of error within one standard deviation. At 24 hr the ranges in nautical miles of north-south error within one standard deviation are: -130 to 190 for HATRACK, -225 to 265 for MOHATT, and -37 to 151 for STATRAK. Thus STATRACK offers the most favorable range of forecast errors at 24 hr. Since MOHATT has both smaller means and standard deviations than HATRACK at 48 hr, only a comparison of ranges between STATRAK and MOHATT is made. At 48 hr the ranges of error in nautical miles within one standard deviation are: -218 to 330 for MOHATT and -133 to 313 for STATRAK. Thus STATRAK also produced a more favorable range of north-south errors at 48 hr. At 72 hr both the STATRAK north-south mean and standard deviation are smaller than the same parameters as generated by MOHATT and HATRACK. Thus the STATRAK model does have some skill in reducing the north-south bias.

As at 500 mb, the STATRAK model's skill, despite large differences in the north-south biases of the two samples, may be due to the ability

TABLE IV

The means and standard deviations (n mi) of the components of errors computed from the 700 mb independent sample.

EAST-WEST ERROR (N MI)

	HATRACK		MOHATT		STATRAK	
	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
24 hr	47	110	95	146	-21	86
48 hr	98	292	54	292	-25	271
72 hr	127	446	88	447	6	435

Note: Positive errors indicate forecast east of best track.

NORTH-SOUTH ERROR (N MI)

	HATRACK		MOHATT		STATRAK	
	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
24 hr	30	160	20	245	47	104
48 hr	89	331	56	274	90	223
72 hr	153	475	134	414	120	328

Note: Positive errors indicate forecast south of best track.

to relate past HATRACK performance with its future performance. As seen in Appendix B, selection of predictors computed from backward integrations is frequent in the equations to 48 hr, and only two equations did not contain such predictors (DXER48 and DXER60). The predictor BYER12 appears in every north-south predictand equation, which also occurred at 500 mb. The BYER12 predictor made the largest contribution to R^2 in the first four of the north-south equations. In the DYER60 and DYER72 equations, the contribution to R^2 by BYER12 was exceeded by only one predictor, VX2448. Thus BYER12 appears to be a key predictor for overcoming HATRACK's north-south bias.

In the east-west predictand equations, BYER12 is common at 12, 24 and 36 hr, while XXLAT is commonly selected for the 48, 60 and 72 hr equations. However, the contributions to R^2 of BYER12 and XXLAT ranged only from 0.04 to 0.11. The dominant contributions to R^2 in the east-west equations occurred with selection of a variety of velocity predictors computed from forward integration data. Therefore the STATRAK model's skill in removing east-west bias does not depend as heavily on past performance of the HATRACK model as does its skill in removing north-south bias.

A comparison of the means of error vector lengths (Fig. 8) shows that the STATRAK model improves the forecast at every time interval. The plots of STATRAK mean vector length errors from the dependent sample shown in Fig. 8 may represent the mean limit of the amount of bias that regression equations can remove at 700 mb.

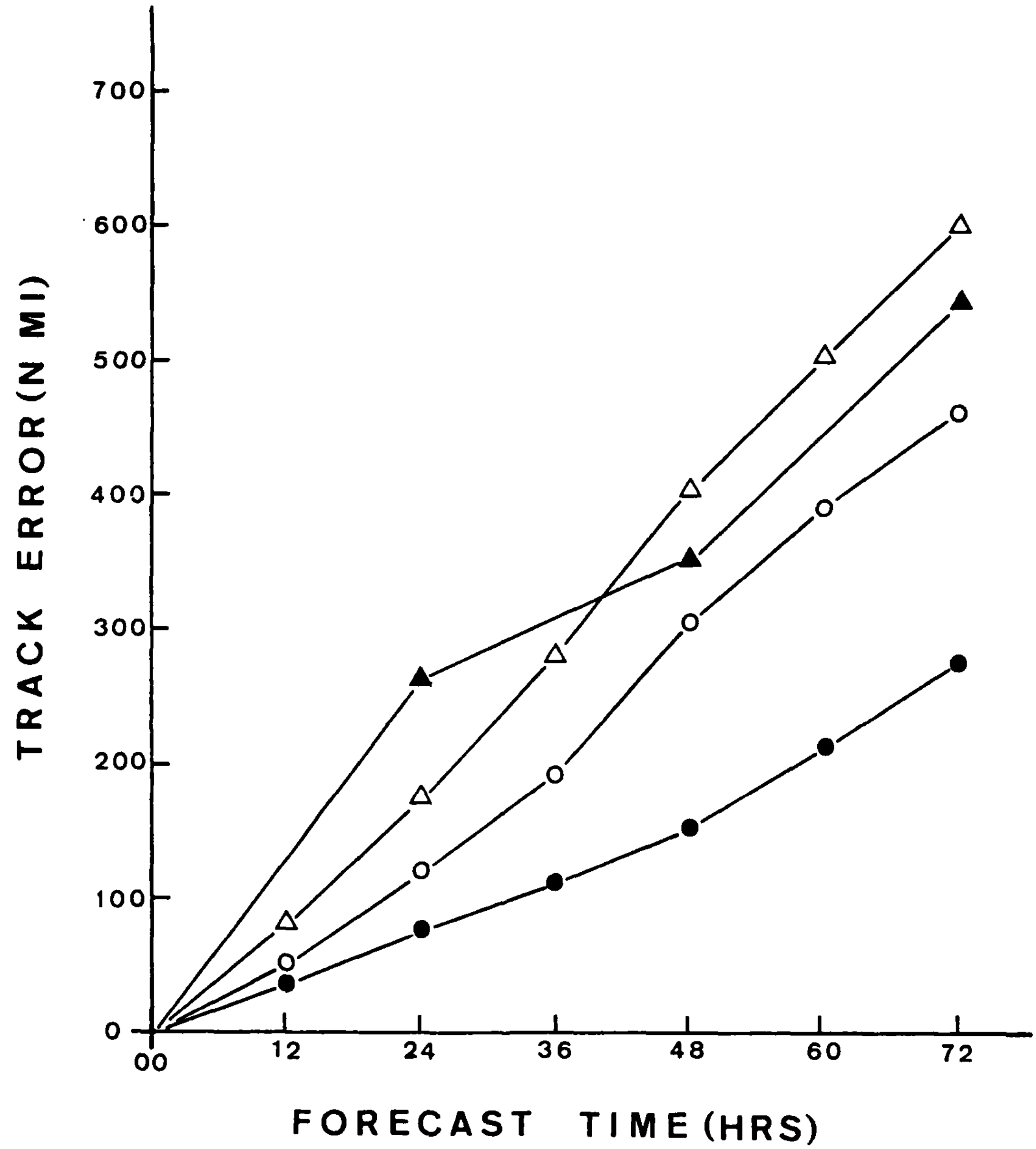

Figure 8. Means of the error vector lengths calculated from the 700 mb independent sample for HATRACK forecasts (△), MOHATT forecasts (▲), STATRAK forecasts (○), and from the 700 mb dependent sample for STATRAK (●).

Details of these means of vector error and the associated standard deviations are given in Table V. The STATRAK model provides either an improvement or no significant change in the standard deviations at all intervals for 700 mb. The values of the standard deviations coupled with smaller means at all intervals underscores the skill of the STATRAK model in removing HATRACK bias.

C. AT 850 MB

A test with 60 storms from the 850 mb dependent sample was performed, and the resulting mean component errors plotted (see Fig. 9). The HATRACK forecast errors do not increase systematically through each time interval as in the dependent samples for 500 and 700 mb. The 850 mb dependent sample HATRACK east-west error is considerably diminished after 48 hr. The north-south 850 mb HATRACK errors are also greatly reduced after 48 hr in this dependent sample. Although this trend in the north-south bias is analogous to that seen in the 700 mb dependent sample (Fig. 6), the magnitude of improvement after 48 hrs is much greater at 850 mb. With respect to HATRACK error, it appears that the 850 mb level would be better than the 700 or 500 mb levels which are advocated in the Naval Weather Service Numerical Environmental Products Manual (1975). This 850 mb dependent sample affords an excellent opportunity to test the STATRACK scheme with a less systematic bias.

The MOHATT model does not perform consistently well in removing HATRACK bias in this sample. The HATRACK north-south errors are made worse by the MOHATT model at all time intervals. The introduction of

TABLE V

The means and standard deviations (n mi) of the errors computed from the 700 mb independent sample.

	HATRACK		MOHATT		STATRAK	
	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
12 hr	83	50	--	--	52	41
24 hr	176	93	266	134	121	75
36 hr	281	137	--	--	194	112
48 hr	405	207	353	195	306	200
60 hr	506	273	--	--	391	261
72 hr	603	300	546	300	464	300

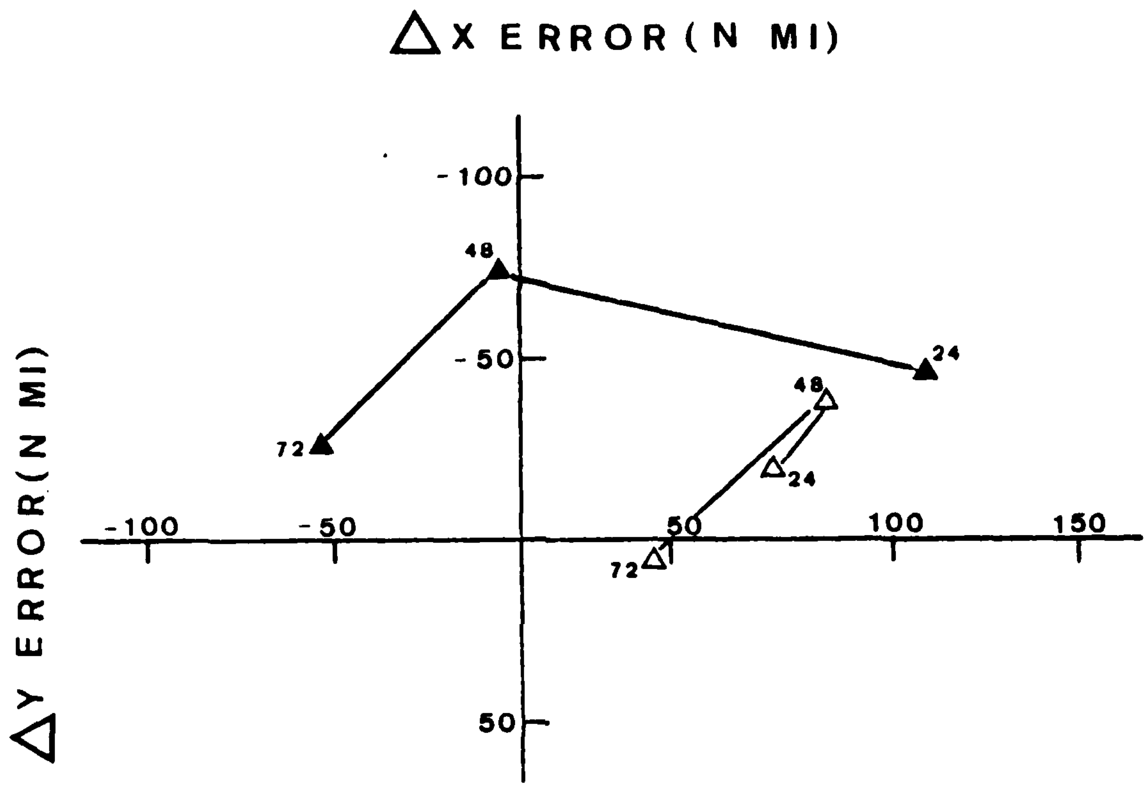

Figure 9. Mean errors of the HATRACK model (Δ) and the MOHATT model (▲) in component form calculated from the 850 mb dependent sample.

north-south error at 72 hr by the MOHATT model, where the HATRACK error is very small, is analogous to the MOHATT behavior in the 500 mb dependent sample. As before, this may reflect a weakness of the MOHATT model in applying a bias correction where little or no bias exists.

The test (see Fig. 10) with the 31 storm independent sample shows a more systematic HATRACK bias, particularly along the north-south component, than was seen in the dependent sample. In the independent sample, the HATRACK model consistenly moved storms too slowly northward with a mean error exceeding 150 nautical miles at 72 hr. The east-west HATRACK mean errors in this independent sample were the smallest encountered in any sample in this study. The values at 24, 48 and 72 hr are so near zero that it would be difficult for any correction scheme to improve the east-west component.

In this independent sample, the MOHATT model made small corrections to the north-south HATRACK bias at all time intervals. In the east-west direction, the MOHATT model introduced larger errors at all time intervals.

The STATRAK mean errors for this independent sample are also shown in Fig. 10. The HATRACK north-south mean errors are not improved by the STATRAK model at 24 and 48 hr, but a substantial improvement in the mean error is gained at 72 hr. The east-west STATRAK errors are comparable in magnitude to those of HATRACK at all time intervals.

The means and standard deviations of the component errors are given in TABLE VI. As the MOHATT model has larger standard deviations than

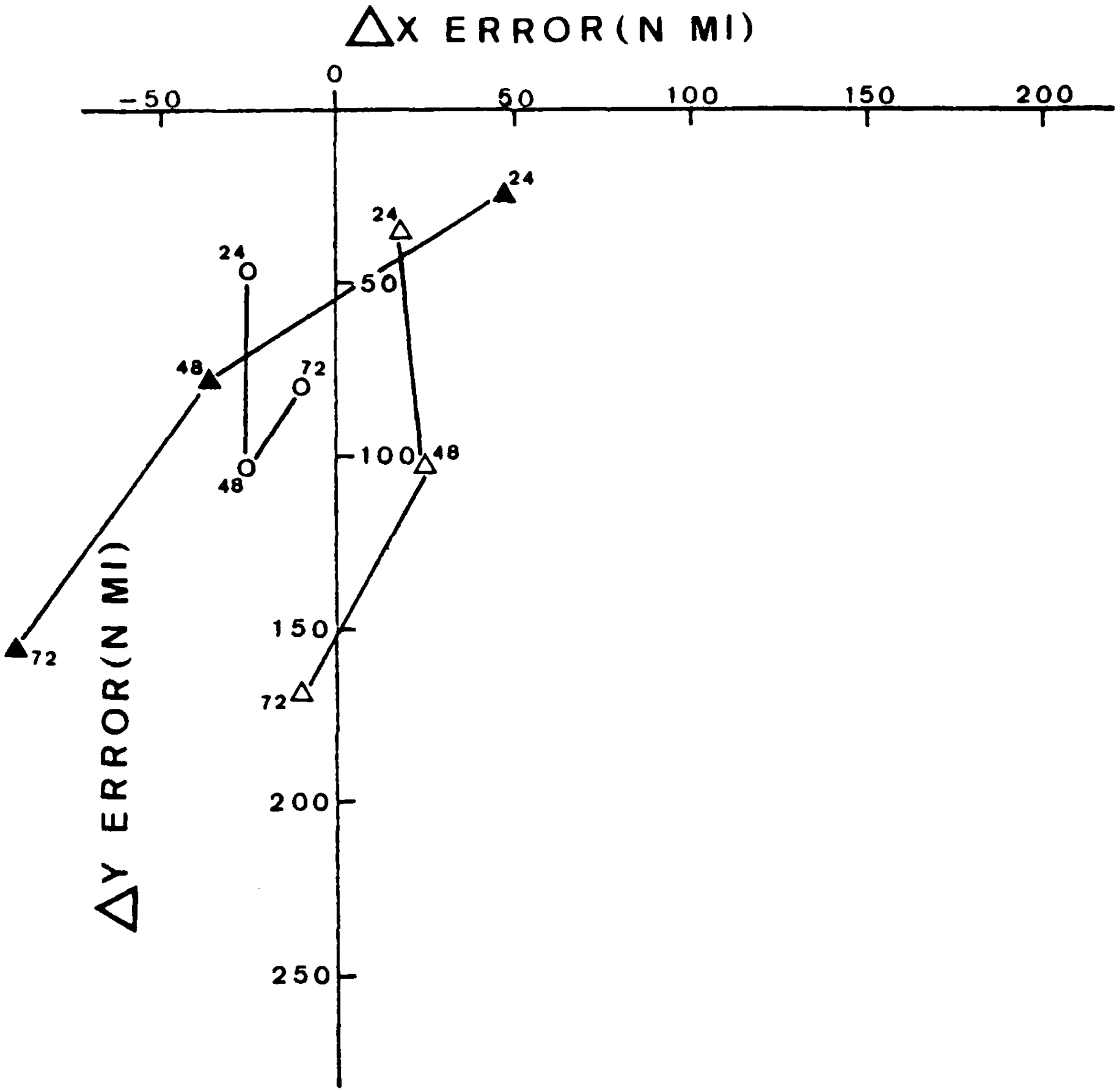

Figure 10. Mean errors of the three models in component form calculated from the 850 mb independent sample relative to best track positions. The plots for HATRACK errors (△) and MOHATT errors (▲) indicate a systematic bias. The plots for STATRACK errors (O) show a reduction of the bias.

TABLE VI

The means and standard deviations (n mi) of the components of errors computed from the 850 mb independent sample.

EAST-WEST ERROR (N MI)

	HATRACK		MOHATT		STATRAK	
	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
24 hr	19	107	48	137	-25	79
48 hr	25	301	-36	318	-35	262
72 hr	-10	489	-92	507	-10	468

Note: Positive values indicate forecast east of best track.

NORTH-SOUTH ERROR (N MI)

	HATRACK		MOHATT		STATRAK	
	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
24 hr	35	158	23	238	45	102
48 hr	102	347	77	299	102	241
72 hr	167	506	155	439	80	359

Note: Positive values indicate forecast south of best track.

the HATRACK model has for the east-west errors at all time intervals, the appropriate comparison is between the HATRACK and STATRAK models. Also, the appropriate comparison is based on the standard deviations since the means provided by both models are close to zero. The standard deviations provided by STATRAK are 20 to 40 nautical miles smaller than are those of HATRACK at all intervals. One may conclude, for this independent sample, that the STATRAK model provides the most desirable distribution of east-west errors for all time intervals. For the north-south errors in this sample, MOHATT provides improvements in both the mean and standard deviation over HATRACK at all time intervals. Therefore, the comparison is made between MOHATT and STATRAK. At 24 hr the MOHATT model presents a one standard deviation north-south range of -215 to 261 while the STATRAK model produces the more desirable range of -57 to 147 nautical miles. At 48 hr, the MOHATT model has a range of -222 to 376 while the STATRAK model yields a range of 138 to 344 nautical miles. The MOHATT model at 72 hr has a larger mean and a larger standard deviation than does STATRAK, and a comparison of ranges is not necessary. Thus in both components of error in this independent sample the STATRAK model offers the most favorable distributions and thereby demonstrates skill at 850 mb.

It should be emphasized that the STATRAK model demonstrates skill at 850 mb despite the significant differences between the north-south HATRACK errors in the dependent and independent samples. An examination of the regression equations (Appendix C) reveals that predictors

computed from backward integration data appear in every equation. However, selection of such "backward" predictors does not dominate the contribution to R^2 in any of the equations, except those for DXER12 and DYER12. Further, the selection of predictors computed from backward integrations at 850 mb generally contribute less to the R^2 values than does selection of such predictors at 700 and 500 mb. The BYER12 predictor appears in every north-south predictand equation; however, selection of BYER12 dominates the contribution to R^2 in only the DYER12 equation. This contrasts sharply with the other levels, where BYER12 dominated the contribution to R^2 in four of the 700 mb north-south equations, and in all of the 500 mb north-south equations. It appears that at the lower steering levels, the BYER12 predictor has a diminishing importance in terms of R^2, yet it is a consistently selected predictor.

The large number of backward integration derived predictors that appear in the equations indicates a continuing ability of the STATRAK model to relate the past HATRACK performance with its future performance as was noted at 700 and 500 mb. Though the role of predictors computed from prior data may be diminished in terms of the R^2 parameter, they do appear to add to the model's skill.

The STATRAK model's skill at 850 mb is also demonstrated by the means of error vectors computed from the independent sample (Fig. 11). As at the other levels, the STATRAK model provided a smaller mean error vector at every time interval than did the MOHATT or HATRACK models. As before, the STATRAK mean error vectors from the independent sample are

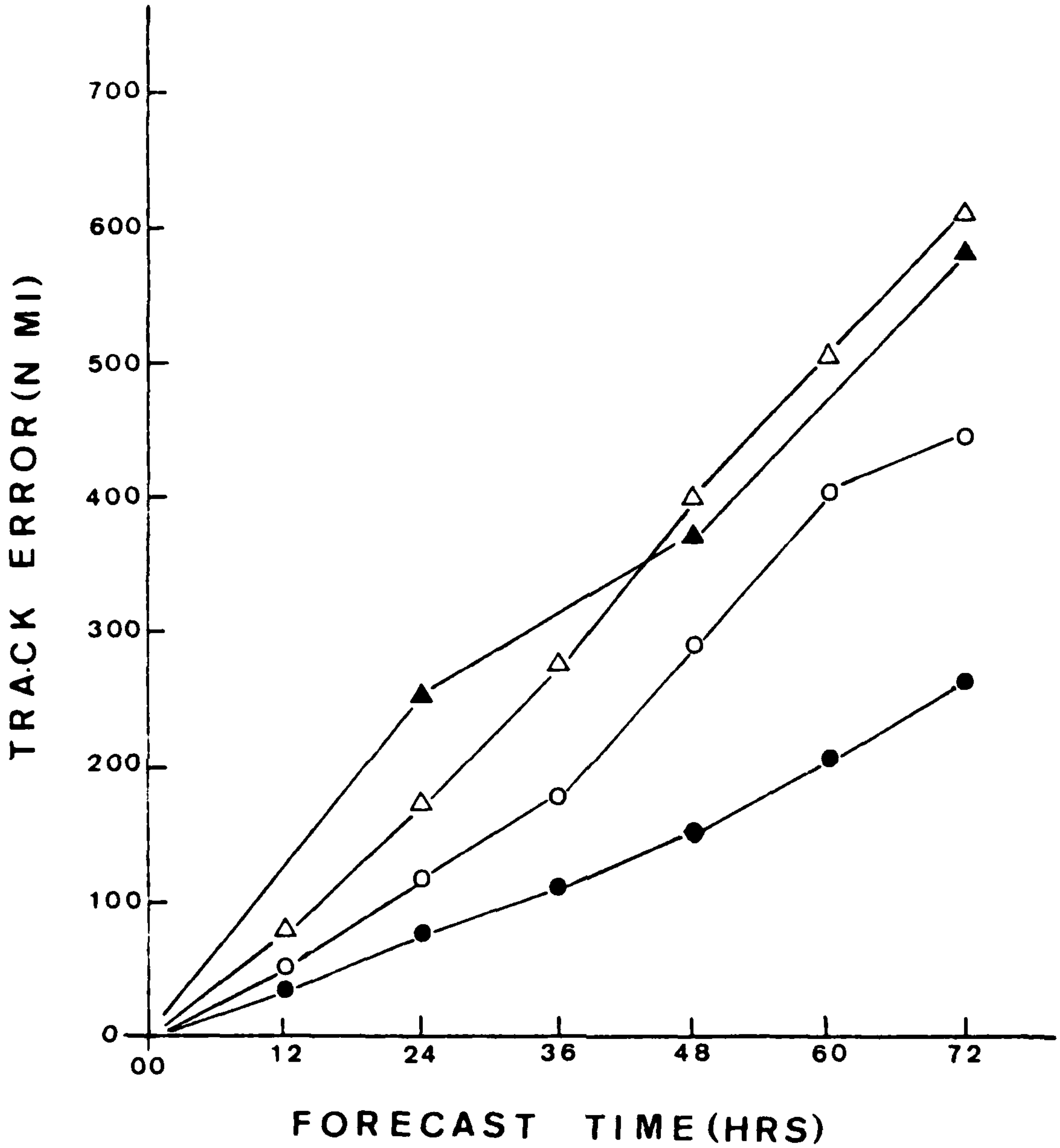

Figure 11. Means of the error vector lengths calculated from the 850 mb independent sample for HATRACK forecasts (△), MOHATT forecasts (▲), STATRAK forecasts (O), and from the 850 mb dependent sample for STATRAK (●).

larger than those from the dependent sample. This is thought to be due to the different behavior of the north-south components between the two samples, although it may also indicate that larger samples are required for the derivation of the regression equations.

Details of these means of vector error and the associated standard deviations are given in Table VII. The STATRAK model provided smaller means and standard deviations of the error vector lengths at every time interval than did either the HATRACK or MOHATT models. These parameters provide further evidence of the STATRAK model skill in removing HATRACK bias at 850 mb.

D. COMPARISON OF 500, 700 AND 850 MB

As shown above, the STATRAK model demonstrates skill in removing HATRACK bias at each of the three levels. A secondary objective of this thesis is to determine whether the 500, 700 or 850 mb steering flow would provide the smallest forecast error. The same 31 storms were chosen as the independent sample at each level so that the comparisons could be performed.

The statistics at 850 mb given above show the HATRACK model provided the smallest mean east-west errors in both the dependent and independent samples. In terms of the mean component errors, there was also a slight advantage at the 850 mb level for the STATRACK model.

For convenience in comparing the STATRAK model's skill, the means and standard deviations of the error vector lengths for each level are summarized in Table VIII. Each level has comparable means and standard

TABLE VII

The means and standard deviations (n mi) of the errors computed from the 850 mb independent sample.

	HATRACK		MOHATT		STATRAK	
	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
12 hr	80	43	--	--	51	37
24 hr	173	84	254	108	118	71
36 hr	277	142	--	--	179	131
48 hr	401	238	373	232	292	223
60 hr	507	331	--	--	405	285
72 hr	611	373	584	361	448	331

TABLE VIII

Summary of the means and standard deviations (n mi) of STATRAK errors computed from independent samples at 500, 700 and 850 mb.

	500 MB		700 MB		850 MB	
	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
12 hr	56	44	52	41	51	37
24 hr	124	84	121	75	118	71
36 hr	208	121	194	112	179	131
48 hr	317	193	306	200	292	223
60 hr	432	246	391	261	405	285
72 hr	533	273	464	300	448	331

deviations at 12 hr, but the differences between these parameters appear to grow in time. To check this possibility, an examination of the one standard deviation ranges is made. These ranges have widths at 12 hr of 112, 104 and 102 nautical miles for 500, 700 and 850 mb, respectively, and they do not appear significantly different. At 72 hr the range widths are 1066, 928 and 896 for 500, 700 and 850 mb respectively. Thus differences between the distributions of errors for the three levels has grown in this test. The 850 mb level might appear to offer the best distributions of errors. In addition to offering the most favorable range at 72 hr, the 850 mb level also provides the smallest mean except at one time interval. However, the differences between the distributions, even at 72 hr. do not appear to be significant.

Appropriate statistical tests to determine whether the means at any interval are generated by the same underlying distribution would require the assumption of normality. Histograms of the vector errors for the independent sample of 31 storms show the variates do not appear to be normally distributed. The east-west and north-south components of STATRAK errors also do not appear Gaussian; and in fact, many of the east-west distributions appear to fit the uniform distribution. Hence a satisfactory statistical test cannot be performed.

However, the small differences in the parameters in Table VIII strongly suggests an approach to same distribution for all three levels. Further tests with larger samples, that may approach normality, might show that the STATRAK model provides equivalent results at all levels.

V. CONCLUSIONS

The objective of this thesis was to develop equations through a multivariate linear regression analysis to improve the HATRACK model forecasts. For convenience, the name STATRAK is given to the method. Dependent samples of 60 and 61 storms from 1967 to 1974 were used to compute 12 predictands and 56 predictors for the regression analysis. The initial radius, latitude, longitude and Julian day provided four of the predictors, 30 were derived from the 12-hour HATRACK forecasts to 72 hr, and 22 were computed from a backward integration of the HATRACK model to -36 hr. The predictands which lead to 12 regression equations are the latitudinal/longitudinal components of the forecast displacements from best track positions.

The analysis was separately performed for HATRACK steering at 500, 700 and 850 mb, and tests were conducted with an independent sample of 31 storms.

Data availability dictated the use of analyzed winds as input to the HATRACK model, rather than the forecast winds from the FNOC Primitive Equation Model. This "perfect-prog" technique greatly reduced the computer time required for this study, but did not allow the regression scheme to correct any additional biases which may arise from the use of forecast winds.

Results show the regression equations of the STATRAK model remove substantially more bias from HATRACK forecasts than does the MOHATT model at 500, 700 and 850 mb. The model skill is most evident through

analyses of the mean north-south and east-west components of forecast error, which reveal improved error distribution parameters at all three levels. The STATRAK improved error components are obtained through displacement predictands which show ability to relate past HATRACK model performance with its future performance.

The STATRAK means of error lengths from a dependent sample establish what is probably the mean limit of the amount of HATRACK bias that the equations can remove. It is important to note that this mean limit to the bias removal appears to be the same at all three levels. This mean limit is compared in Table IX to the annual official forecast errors for the same years of storm data used in this study. The annual errors include a wide variety of situations, and these numbers should only be used as an indication of typical errors rather than as a direct comparison with the STATRAK model. For the 24 and 48 hr forecasts, the STATRAK means are below the range of annual official forecast errors. At 72 hr, the STATRAK means fall in the lower part of the range of annual official forecast errors. At every time interval, the STATRAK means are notably lower than the five-year running mean.

The mean vector STATRAK errors for the independent sample were considerably larger than in the dependent sample, although the STATRAK model had better error statistics than the HATRACK and MOHATT models. The larger errors may be traced to the significant differences in the behavior of HATRACK north-south bias between dependent and independent samples. Independent samples of randomly selected storms should have

TABLE IX

The range of annual official forecast errors (n mi) for the years 1967 to 1974, the five-year running mean of official forecast errors (n mi) as computed in 1972, and the STATRAK means of vector errors (n mi) computed from the 500, 700 and 850 mb dependent samples. (Annual Typhoon Report, 1974).

	1967-1974 RANGE OF OFFICIAL FORECAST ERRORS (N MI)	THE 1972 FIVE-YEAR RUNNING MEAN (N MI)	STATRAK ERROR VECTOR MEANS (N MI)		
			500 MB	700 MB	850 MB
24 hr	98 - 125	110	71	78	79
48 hr	181 - 276	210	144	151	155
72 hr	245 - 414	315	261	278	265

manifested HATRACK biases similar to those found in the larger dependent sample. It is anticipated that further tests with new samples should provide STATRAK errors which approach the mean limit demonstrated for the dependent sample.

The STATRAK model vector error distributions at 500, 700 and 850 mb show striking similarities and appear to be approaching a common underlying distribution. The independent samples were too small to show an approach to the Gaussian distribution, and statistical tests could not be performed to determine whether the means from the samples at different levels were equivalent. Therefore the designation of a best level could not be made. Further tests should be conducted to select or combine the three steering levels to provide the best possible STATRAK guidance to the typhoon forecasters.

APPENDIX A. THE 500 MB REGRESSION EQUATIONS

The regression equations which follow were produced by the BMPD stepwise regression routine using predictors derived from both forward and backward integrations of the HATRACK model. The data sample consisted of 60 storms, one case per storm, using 500 mb steering. Also shown is the value of R^2 as computed by the BMPD routine for each equation.

REGRESSION EQUATIONS	R^2
DXER12 = -12.8162 + 6.8983(RADIUS) - 0.4244(BXER12)	0.26
DYER12 = - 2.8689 - 0.7342(BYER12) - 1.8503(VX2436) + 2.5889(VY2436) - 9.8690(VY0012) + 6.7154(VYM200)	0.85
DXER24 = +81.2477 + 10.5985(RADIUS) - 3.5651(XXLAT) + 0.5967(BYER12) + 7.8947(VY0036) - 8.8311(VX1224)	0.48
DYER24 = - 9.4730 - 1.4647(BYER12) + 20.7137(VY1236) - 4.8133(VX2436) - 28.2767(VY1224) + 4.8820(VYM200)	0.88
DXER36 = +170.2834 - 5.6729(XXLAT) + 0.6991(BYER12) + 17.2930(VY0048) - 11.5743(VX2436)	0.47
DYER36 = +50.8722 - 9.7568(RADIUS) - 2.0832(BYER12) - 9.1510(VX2448) - 12.7337(VY1224) + 5.4185(VXM4M2)	0.87
DXER48 = +229.0410 - 7.8989(XXLAT) + 0.8762(BYER12) - 14.1854(VX2448) + 20.0146(VY2448)	0.48
DYER48 = +72.1908 - 14.3688(RADIUS) - 2.8611(BYER12) - 10.9403(VX2448) - 14.3196(VY1224) + 6.4846(VXM4M2)	0.83
DXER60 = +314.3184 - 14.6053(XXLAT) - 16.7638(VX4872) + 24.3995(VY2448)	0.46
DYER60 = +51.8976 - 3.5148(BYER12) - 25.3468(VY0072) - 13.9597(VX2436) + 9.3034(VXM4M2)	0.75
DXER72 = +503.9778 - 22.0040(XXLAT) + 0.6877(BYER36) - 26.1517(VX6072) + 21.5005(VY2448)	0.52
DYER72 = +59.8970 - 4.4847(BYER12) - 18.8023(VY6072) - 13.8656(VX2436)	0.69

APPENDIX B. THE 700 MB REGRESSION EQUATIONS

The regression equations which follow were produced by the BMPD stepwise regression routine using predictors derived from both forward and backward integrations of the HATRACK model. The data sample consisted of 61 storms, one case per storm, using 700 mb steering. Also shown is the value of R^2 as computed by the BMPD routine for each equation.

REGRESSION EQUATIONS	R^2
DXER12 = +10.4547 - 0.4513(BXER12) + 3.2678(VY1224) - 20.7509(VYM4M2) + 18.9771(VYM600)	0.48
DYER12 = -5.5459 - 0.6339(BYER12) - 2.9682(VX2436) - 12.6166(VY0012) + 1.5356(VXM4M2) + 11.5677(VYM424)	0.83
DXER24 = +16.1241 - 0.5389(BXER12) + 12.8010(VY0036) - 4.1051(VX2436) - 9.3874(VYM4M2)	0.45
DYER24 = -19.6180 - 1.3244(BYER12) - 6.5472(VX2436) + 34.2421(VYM200) - 36.0802(VYM212) + 2.5930(VXM6M2)	0.85
DXER36 = +9.9539 - 0.8720(BXER12) + 15.8137(VY2448) - 7.5326(VX2436) - 9.6239(VYM4M2)	0.45
DYER36 = +36.8283 - 11.2840(RADIUS) - 2.2036(BYER12) - 8.0964(VX2448) - 13.9182(VY1224) + 8.7598(VYM200)	0.82
DXER48 = +174.3695 - 8.3050(XXLAT) - 11.1934(VX3648) + 22.1957(VY3648)	0.44
DYER48 = +733.3269 - 20.4927(RADIUS) - 2.7408(XXLON) - 2.6558(BYER12) - 17.7363(VY0072) - 12.4351(VX2436)	0.79
DXER60 = +190.7207 - 11.2922(XXLAT) - 13.1144(VX3648) +31.4787(VY3648)	0.43
DYER60 = +59.5088 - 2.8872(BYER12) - 26.8289(VY0072) - 15.5643(VX2448)	0.66
DXER72 = +198.4792 - 15.0706(XXLAT) - 0.4932(BXER36) - 13.9042(VX3660) + 35.7415(VY3648)	0.45
DYER72 = +63.6688 - 3.1991(BYER12) - 23.6189(VY3660) - 21.0556(VX2448)	0.57

APPENDIX C. THE 850 MB REGRESSION EQUATIONS

The regression equations which follow were produced by the BMPD stepwise regression routine using predictors derived from both forward and backward integrations of the HATRACK model. The data sample consisted of 61 storms, one case per storm, using 850 mb steering. Also shown is the value of R^2 as computed by the BMPD routine for each equation.

REGRESSION EQUATIONS	R^2
DXER12 = +5.7176 - 1.2511(BXER12) + 0.3501(BXER24) + 4.3116(VY1236) - 4.8646(VYM600)	0.63
DYER12 = +119.4558 - 0.4993(XXLON) - 0.6121(BYER12) - 2.7909(VX2448) - 9.8775(VY0012) + 7.2710(VYM424)	0.84
DXER24 = -22.0921 - 1.9628(BXER12) + 0.5952(BXER24) - 0.2406(BYER36) + 8.4626(VY2436)	0.57
DYER24 = +8.6041 - 1.2350(BYER12) - 5.9170(VX2436) - 13.9160(VY0024) + 9.8478(VYM200)	0.82
DXER36 = -25.8162 - 0.9034(BXER12) + 18.1259(VY3648) - 9.7848(VX2436) + 7.5139(VXM200) - 10.0986(VYM600)	0.65
DYER36 = +25.6343 - 1.9390(BYER12) - 21.8738(VY0048) - 8.1353(VX2436) + 13.6415(VYM200)	0.79
DXER48 = -44.4923 - 0.9935(BXER12) + 28.0816(VY3660) - 11.7773(VX3648) - 15.2161(VYM600)	0.66
DYER48 = +46.1028 - 2.5646(BYER12) - 30.7881(VY0048) - 8.8038(VX2448) + 17.9989(VYM200)	0.74
DXER60 = +104.1494 - 11.9843(XXLAT) - 0.3195(BXER36) + 38.4615(VY3660) - 18.5504(VX4860)	0.66
DYER60 = +93.7865 - 3.0922(BYER12) - 43.9506(VY0072) - 9.8677(VX2448) + 25.0571(VYM200)	0.66
DXER72 = +146.2080 - 16.7482(XXLAT) - 0.8099(BXER24) - 23.7028(VX6072) + 41.9161(VY4860)	0.62
DYER72 = +124.2110 - 3.4222(BYER12) - 69.2770(VY0072) - 12.4532(VX2448) + 53.3299(VYM424)	0.59

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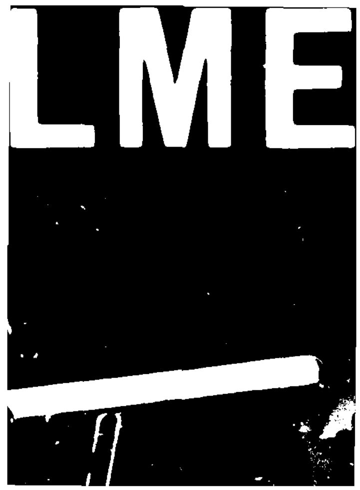
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